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Experimental studies of the seismic behavior of double-layer lattice space structures I: Experimental verification

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A B S T R A C T

Double-layer lattice space structures were found in a severe state of damage following the 2013 M7.0 Lushan earthquake in China. The failure of this kind of structure can result in huge damage and extensive repair costs. Therefore, the accurate definition of degrees of structural damage in double-layer lattice space structure is of high interest, in particular to give a better understanding of failure mechanisms and more accurately implement performance-based designs of these structures. In this paper, typical failure patterns of two gymnasiums are summarized, and possible reasons are broadly discussed. The seismic behavior of a double-layer lattice space structure with a lower supporting structure was then investigated using a shaking table test. To this end, a 1/10 scale model of a double-layer lattice space structure corresponding to the prototype structure with span of 40.8 m was designed. The dynamic characteristics including structure frequencies and damping ratio were obtained through the results under the input excitation of white noises with different amplitudes. Furthermore, two representative earthquake records were used to evaluate the performance and different damage degree by a 5 m × 5 m shaking table. The seismic responses including the acceleration and displacement placed at different height of the model as well as the strain gathered at the members were discussed. Results of the test indicate that the seismic effect is underestimated without considering the dynamic amplification effect of the lower supporting structure, which leads to the failure of structures. Therefore, the lower supporting structure should be considered as an integrated model with the upper structure when conducting seismic analysis and evaluation, rather than considering the lower supporting structure as rigid.

1. Introduction

The lattice space structure, including single-layer and double-layer structures, is one of the most shared structural forms for roof structures of gymnasiums, auditoriums, airplane hangars, exhibition halls and so on. This type of structure has been widely used throughout the world, especially in China in the last three decades. Improving the understanding of the dynamic behavior and failure mechanism of this kind of structure is very important when considering the increased worldwide demand for such structures, since many of them are built in areas of moderate to high seismic activity, such as Japan, the United States, and China. Member buckling and connection dislocation in double-layer lattice steel space structures were observed in the strong seismic events in Kobe (1995) by AIJ [1]. Saka and Taniguchi [2] then showed that the concrete spalling of the lower supporting

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structure was a main reason leading to structural damage. Furthermore, some failure patterns such as buckling of members, fractures of turnbuckles, and concrete spalling at the supports were reported during the Great East Japan Earthquake on March 11, 2011 by AIJ [3,4]. The mechanism behavior of the structural did not vary if the damage only occurred in a few members. However, two typical double-layer lattice steel space structures were found in a state of severe damage onApril 20, 2013, Lushan earthquake in the Sichuan province of China by Nie et al. [5]. One was dismantled, and the other was repaired with extensive costs.

Much work has been done in order to understand the seismic behavior of steel lattice space structures more clearly or provide some useful references for further research and design. The obvious nonlinear geometric effect is believed to be particularly important to the dynamic instability of lattice space structures. Zhi et al. [6] investigated collapse of single-layer lattice structures caused by dynamic instability subjected to harmonic load and seismic load. In order to understand the influence of member buckling on the stability of single-layer lattice structures, a judgment method of member buckling was proposed by Fan et al. [7]. He et al. [8] investigated the elastic–plastic stability of the single-layer cylindrical lattice structure by parametric analysis. To date, more and more researchers focus on structural responses to evaluate the seismic performance of the structure. Li et al. [9] investigated the elasto-plastic dynamic response of single-layer lattice structures under strong earthquake excitation. Then Li et al. [10] investigated the seismic behavior of double-layer lattice structures with respect to geometric parameters. Yang et al. [11] evaluated the seismic behavior of double-layer lattice structures with some selected bars replaced by passive viscoelastic dampers. Altuna Zugasti et al. [12] and Cai et al. [13] also studied the seismic behavior of different kinds of space lattice structures with different structural parameters. After that, Zhi et al. [14] and Nie et al. [15] conducted vulnerability and risk assessment of single-layer lattice structures subjected to different earthquake motions and obtained the corresponding vulnerability curve.

Through numerical simulations, the foregoing studies have improved the understanding on dynamic responses and failure mechanisms of steel lattice space structures during earthquakes. However, experimental studies are another effective way to understand and validate theoretical studies and numerical simulations. Nie et al. [16] defined a normalized constitutive model to consider material damage accumulation of space lattice structures under earthquakes through experimental study. Nie et al. [17–18] then investigated the static mechanical performance of double-layer lattice structures and the seismic performance of single-layer lattice structures based on static loading experiments and shaking table tests. However, little attention was paid to failure patterns and seismic behavior of double-layer lattice structures under seismic motion, although this kind of structure is the most widely used structural form.

This paper summarizes the typical failure patterns of two double-layer lattice space structures and discusses the possible reasons. Then the dynamic characteristics and seismic behavior of a scaled-down model of a double-layer lattice space structure are investigated by a shaking table test. Furthermore, the different damage states of the structure are analyzed and discussed, as are the seismic responses, including the acceleration and displacement at different heights of the model as well as the strain gathered at the members. Results of the test indicate that the seismic effect is underestimated without considering the dynamic amplification effect of the lower supporting structure, which leads to structural failure.

2. Failure patterns of the double-layer lattice space structure in the Lushan earthquake

The M7.0 Lushan earthquake occurred on April 20, 2013, resulting in 196 people dead, 24 missing and at least 11,826 injured, with more than 968 seriously injured. Four double-layer lattice space structures were found in a state of damage. Two of them, Lushan gymnasium and Lushan middle school gymnasium, suffered severe damage, and the latter structure was rendered unusable. Some typical failure patterns of the two structures were investigated during this earthquake, which was different from previous earthquakes in China, and even in the world. The Lushan gymnasium and Lushan middle school gymnasium were built after the 2008 M8.0 Wenchuan earthquake, which occurred on the same province of China. The damage of these

(a)Lushan gymnasium (b) Lushan middle school gymnasium

Fig. 1. Appearance of Lushan gymnasium and Lushan middle school gymnasium after the earthquake. (a) Lushan gymnasium. (b) Lushan middle school gymnasium.